Course/Course Code:

Data Acquisition and Microcontroller (MC-546)

Lecture # 02

SENSORS AND TRANSDUCERS

Course Teacher:

Dr. Tariq Rehman

OUTLINE

- ☐ Displacement, Position and Proximity Sensors

1. Potentiometer Sensor
2. Strain-gauged element
3. Capacitive element
4. Differential transformers
5. Eddy current proximity sensors
6. Inductive proximity switch
7. Optical encoders
8. Pneumatic sensors
9. Proximity switches
10. Hall effect sensors

DISPLACEMENT, POSITION AND PROXIMITY SENSORS

- **Displacement sensors** are concerned with the measurement of the mount by which some object has been moved;

- **Position sensors** are concerned with the determination of the position of some object in relation to some reference point.

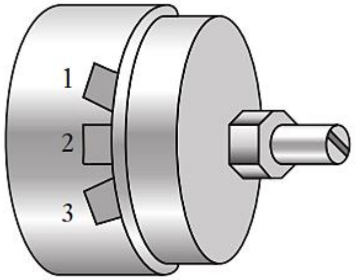
- **Proximity sensors** are a form of position sensor and are used to determine when an object has moved to within some particular critical distance of the sensor. They are essentially devices which give on/off outputs.

1. POTENTIOMETER SENSOR

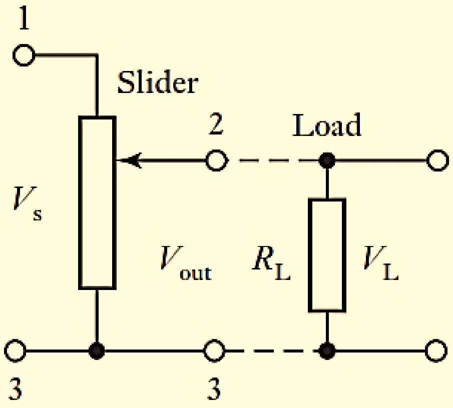
- ☐ A **potentiometer** consists of a resistance element with a sliding contact which can be moved over the length of the element.

- ☐ Such elements can be used for linear or rotary displacements, the displacement being converted into a potential difference.

- ☐ The rotary potentiometer consists of a circular wire-wound track or a film of conductive plastic over which a rotatable sliding contact can be rotated (Figure).



A rotary potentiometer



The circuit when connected to a load

- ☐ The load resistance, R_L is in parallel with the fraction x of R_P i.e. xR_P. The net resistance would be,

$$R_L x R_p/(R_L + xR_p)$$

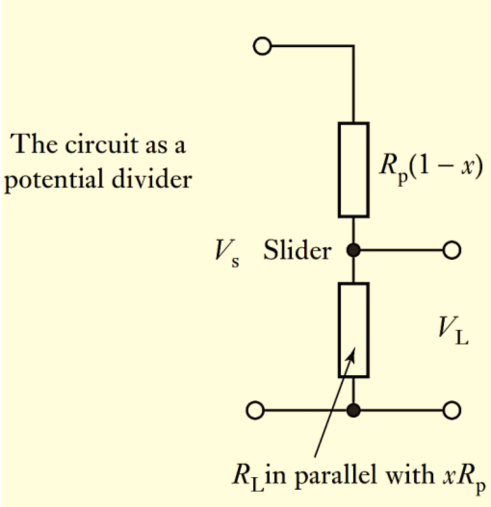
- ☐ The total voltage across the source voltage is,

$$\text{total resistance} = R_p(1 - x) + R_L x R_p/(R_L + xR_p)$$

- ☐ The circuit is a potential divider circuit and thus the voltage across the load is the fraction that the resistance across the load is of the total resistance across which the applied voltage is connected:

$$\frac{V_L}{V_s} = \frac{xR_L R_p/(R_L + xR_p)}{R_p(1 - x) + xR_L R_p/(R_L + xR_p)}$$

$$= \frac{x}{(R_p/R_L)x(1 - x) + 1}$$


The circuit as a potential divider
$R_p(1 - x)$
V_s
Slider
V_L
R_L in parallel with xR_p

If the load is of infinite resistance then we have $V_L = xV_s$. Thus the error introduced by the load having a finite resistance is

$$\text{error} = xV_s - V_L = xV_s - \frac{xV_s}{(R_p/R_L)x(1-x)+1}$$

$$= V_s \frac{R_p}{R_L}(x^2 - x^3)$$

To illustrate the above, consider the non-linearity error with a potentiometer of resistance 500 Ω, when at a displacement of half its maximum slider travel, which results from there being a load of resistance 10 kΩ. The supply voltage is 4 V. Using the equation derived above

$$\text{error} = 4 \times \frac{500}{10\,000}(0.5^2 - 0.5^3) = 0.025\ \text{V}$$

As a percentage of the full range reading, this is 0.625%.

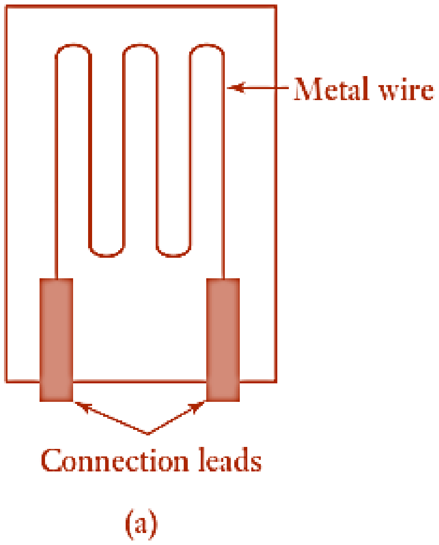
2. STRAIN GAUGED ELEMENT

- The electrical resistance strain gauge (Figure 2.6) is a metal wire, metal foil strip or a strip of semiconductor material which is wafer-like and can be stuck onto surfaces like a postage stamp.

- When subject to strain, its resistance R changes, the fractional change in resistance $\Delta R/R$ being proportional to the strain ε, i.e.

$$\frac{\Delta R}{R} = G\varepsilon$$

where G, *the constant of proportionality, is termed the gauge factor.*



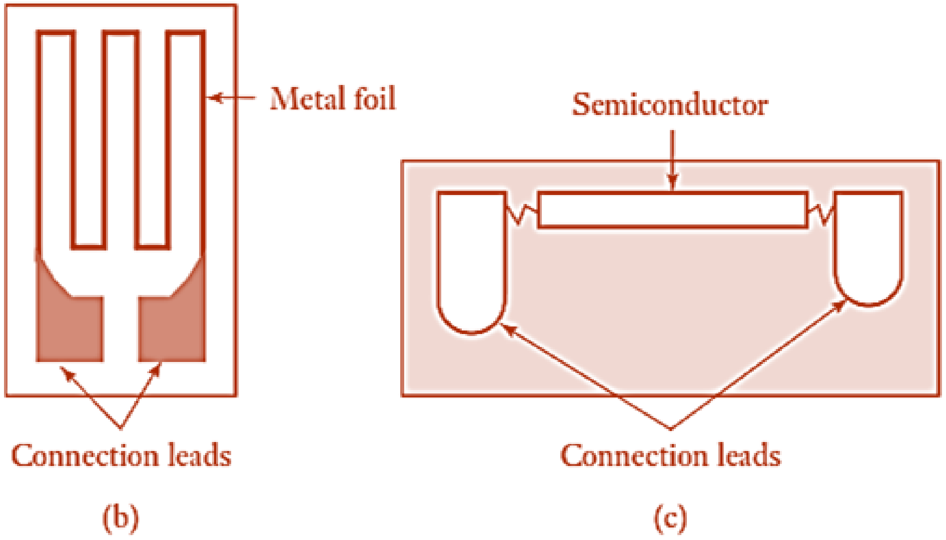


Figure 2.6 Strain gauges: (a) metal wire, (b) metal foil, (c) semiconductor.

- Since strain is the ratio (change in length/original length) then the resistance change of a strain gauge is a measurement of the change in length of the element to which the strain gauge is attached.

- The gauge factor of metal wire or foil strain gauges with the metals generally used is about 2.0 and resistances are generally of the order of about 100 Ω.
- Silicon p- and n-type semiconductor strain gauges have gauge factors of about +100 and −100 respectively.

Example: Consider an electrical resistance strain gauge with a resistance of 100 Ω and a gauge factor of 2.0. What is the change in resistance of the gauge when it is subject to a strain of 0.001? The fractional change in resistance is equal to the gauge factor multiplied by the strain, thus

$$\text{change in resistance} = 2.0 \times 0.001 \times 100 = 0.2\,\Omega$$

STRAIN GAUGE FOR DISPLACEMENT MEASUREMENT

- Displacement sensor has strain gauges attached to flexible elements in the form of cantilevers (Figure 2.7(a)), rings (Figure 2.7(b)) or U-shapes (Figure 2.7(c)).

- When the flexible element is bent or deformed as a result of forces being applied by a contact point being displaced, then the electrical resistance strain gauges mounted on the element are strained and so give a resistance change which can be monitored.

- The change in resistance is thus a measure of the displacement or deformation of the flexible element.
- Such arrangements are typically used for linear displacements of the order of 1 to 30 mm and have a non-linearity error of about ±1% of full range.

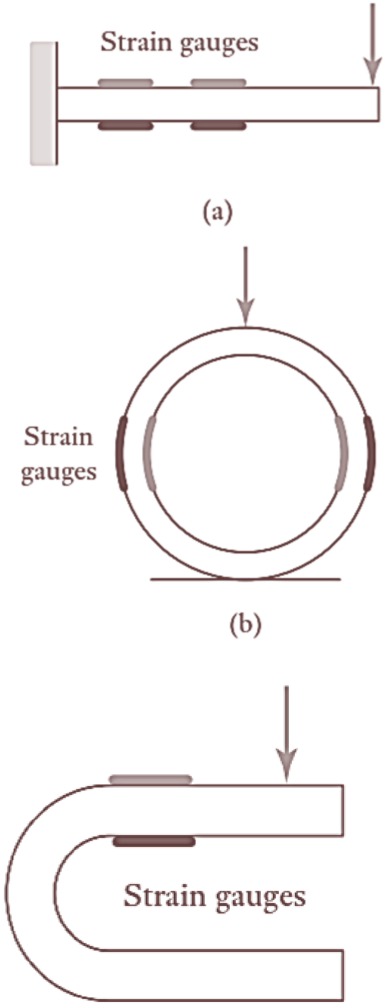


Figure 2.7 Strain-gauged element.

3. CAPACITIVE ELEMENT

The capacitance C of a parallel plate capacitor is given by

$$C = \frac{\varepsilon_r \varepsilon_0 A}{d}$$

where ε_r is the relative permittivity of the dielectric between the plates, ε_0 a constant called the permittivity of free space, A the area of overlap between the two plates and d the plate separation. Capacitive sensors for the monitoring of linear displacements might thus take the forms shown in Figure 2.8.

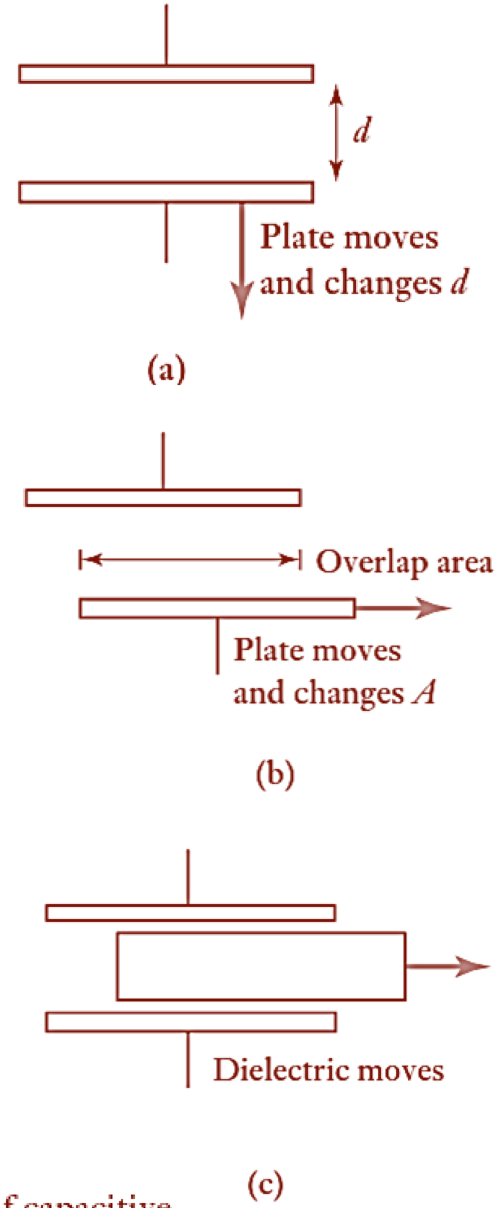


Figure 2.8 Forms of capacitive sensing element.

$$C - \Delta C = \frac{\varepsilon_0 \varepsilon_r A}{d + x}$$

Hence the change in capacitance ΔC as a fraction of the initial capacitance is given by:

$$\frac{\Delta C}{C} = -\frac{d}{d + x} - 1 = -\frac{x/d}{1 + (x/d)}$$

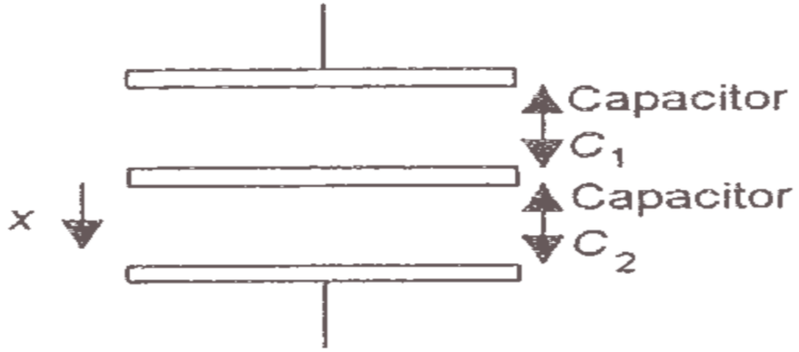


Fig. 2.9 Push-pull sensor

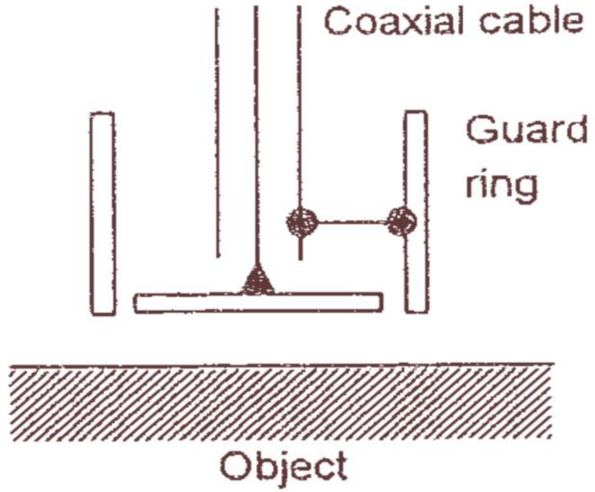


Fig. 2.10 Capacitive proximity sensor

4. DIFFERENTIAL TRANSFORMERS

- The linear variable differential transformer, generally referred to by the acronym LVDT, consists of three coils symmetrically spaced along an insulated tube **(see Figure 2.11).**
- The central coil is the primary coil and the other two are identical secondary coils which are connected in series in such a way that their outputs oppose each other.
- A magnetic core is moved through the central tube as a result of the displacement being monitored.
- The e.m.f. induced in a secondary coil by a changing current i in the primary coil is given by

$$e = M\frac{di}{dt}$$

where *M is the mutual inductance, its value depending on the number of* turns on the coils and the ferromagnetic core.

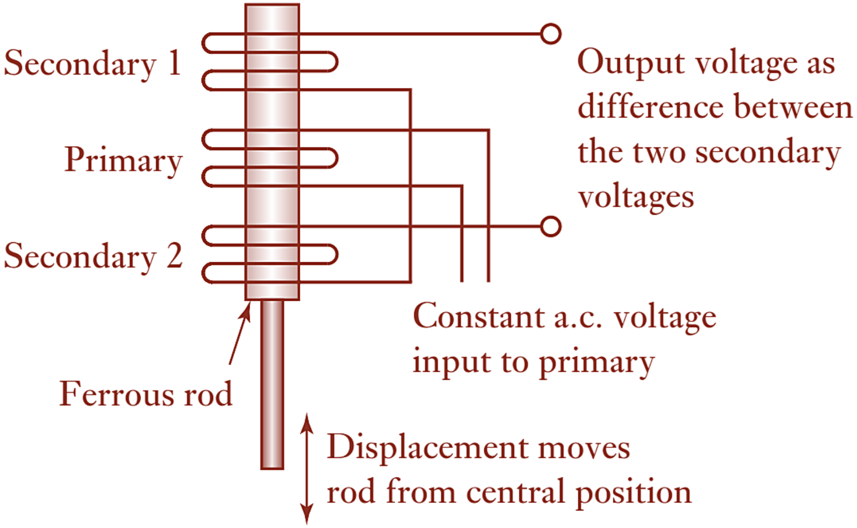

Secondary 1
Primary
Secondary 2
Ferrous rod
Output voltage as difference between the two secondary voltages
Constant a.c. voltage input to primary
Displacement moves rod from central position

Figure 2.11 LVDT.

Thus, for a sinusoidal input current of $i = I \sin \omega t$ to the primary coil, the e.m.f. is induced in the two secondary coils 1 and 2 can be

$$v_1 = k_1 \sin(\omega t - \phi) \text{ and } v_2 = k_2 \sin(\omega t - \phi)$$

where the values of k_1, k_2 and ϕ depend on the degree of coupling between the primary and secondary coils for a particular core position. ϕ is the phase difference between the primary alternating voltage and the secondary alternating voltages. Because the two outputs are in series, their difference is the output

$$\text{output voltage} = v_1 - v_2 = (k_1 - k_2) \sin(\omega t - \phi)$$

When the core is equally in both coils, k_1 equals k_2 and so the output voltage is zero. When the core is more in 1 than in 2 we have $k_1 > k_2$ and

$$\text{output voltage} = (k_1 - k_2) \sin(\omega t - \phi)$$

else

$$\text{output voltage} = -(k_1 - k_2) \sin(\omega t - \phi) = (k_2 - k_1) \sin[\omega t + (\pi - \phi)]$$

5. EDDY CURRENT PROXIMITY SENSORS

- If a coil is supplied with an alternating current, an alternating magnetic field is produced.
- If there is a metal object in close proximity to this alternating magnetic field, then **eddy currents** are induced in it.
- The eddy currents themselves produce a magnetic field. This distorts the magnetic field responsible for their production.
- As a result, the impedance of the coil changes and so does the amplitude of the alternating current. At some preset level, this change can be used to trigger a switch.
- **Figure 2.15** shows the basic form of such a sensor; it is used for the detection of non-magnetic but conductive materials.

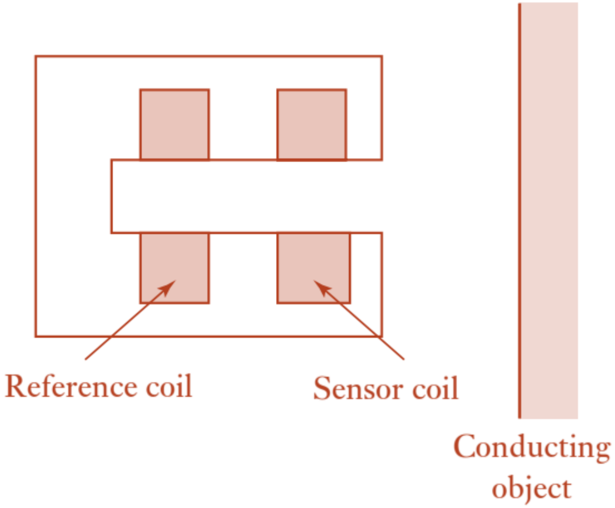


Figure 2.15 Eddy current sensor.

6. INDUCTIVE PROXIMITY SWITCH

- This consists of a coil wound round a core. When the end of the coil is close to a metal object its inductance changes.

- This change can be monitored by its effect on a resonant circuit and the change used to trigger a switch. It can only be used for the detection of metal objects and is best with ferrous metals.

7. OPTICAL ENCODERS

- An **encoder** is a device that provides a digital output as a result of a linear or angular displacement. Position encoders can be grouped into two categories:
    - **incremental encoders**, which detect changes in rotation from some datum position; and
    - **absolute encoders**, which give the actual angular position.

- **Figure 2.16(a)** shows the basic form of an incremental encoder for the measurement of angular displacement. A beam of light passes through slots in a disc and is detected by a suitable light sensor.
- When the disc is rotated, a pulsed output is produced by the sensor with the number of pulses being proportional to the angle through which the disc rotates.
- Thus the angular position of the disc, and hence the shaft rotating it, can be determined by the number of pulses produced since some datum position.

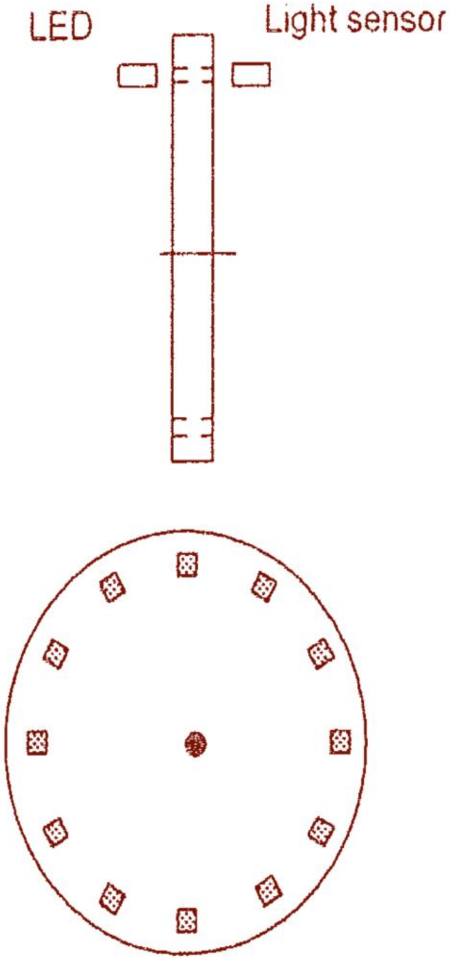


Figure 2.16 Incremental encoder: (a) the basic principle,

Cont..

- In practice three concentric tracks with three sensors are used (**see Figure 2.16(b)**).

- The inner track has just one hole and is used to locate the 'home' position of the disc.

- The other two tracks have a series of equally spaced holes that go completely round the disc but with the holes in the middle track offset from the holes in the outer track by one-half the width of a hole.

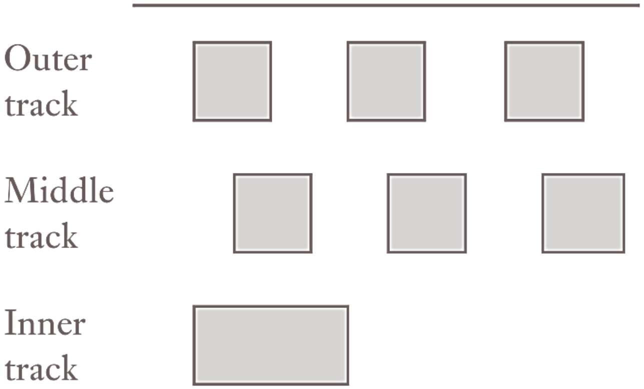


Figure 2.16 (b) concentric tracks.

- This offset enables the direction of rotation to be determined. In a clockwise direction the pulses in the outer track lead those in the inner; in the anti-clockwise direction they lag.

- *The resolution is determined by the number of slots on the disc. With 60 slots in 1 revolution then, since 1 revolution is a rotation of 360°, the resolution is* 360/60 = 6°.

8. PNEUMATIC SENSORS

- Pneumatic sensors involve the use of compressed air, displacement or the proximity of an object being transformed into a change in air pressure.

- **Figure 2.19** shows the basic form of such a sensor. Low-pressure air is allowed to escape through a port in the front of the sensor.

- This escaping air, in the absence of any close-by object, escapes and in doing so also reduces the pressure in the nearby sensor output port.

- However, if there is a close-by object, the air cannot so readily escape and the result is that the pressure increases in the sensor output port. The output pressure from the sensor thus depends on the proximity of objects.

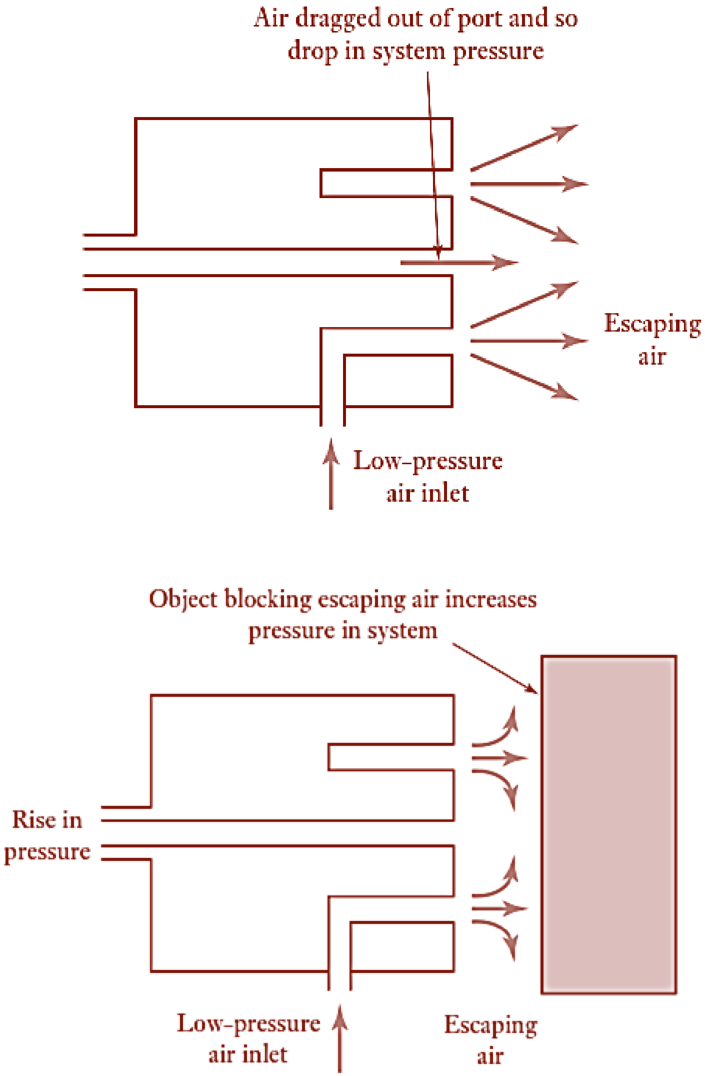
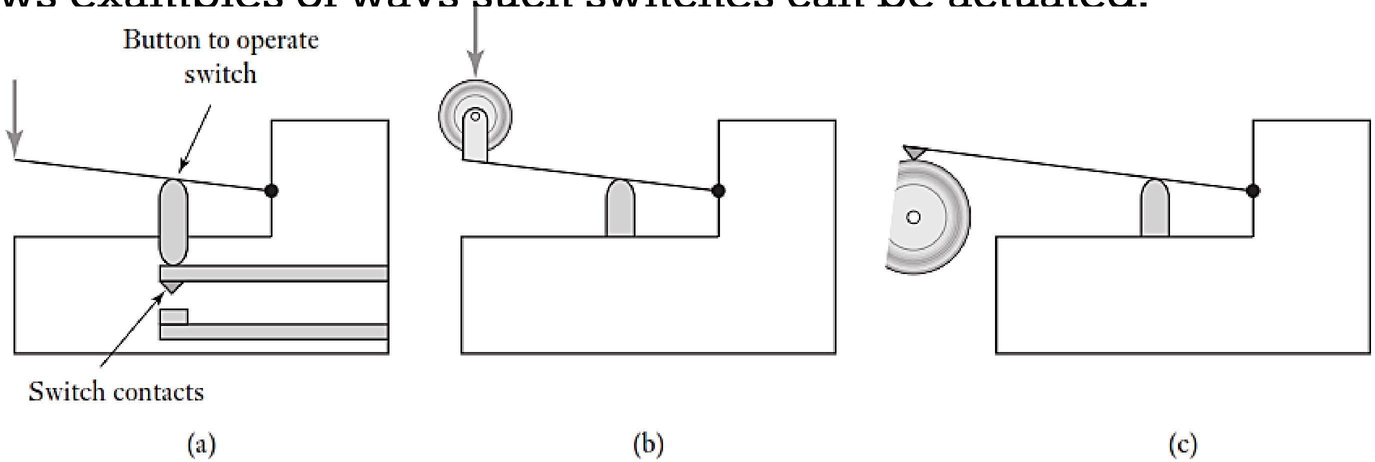

Air dragged out of port and so drop in system pressure
Escaping air
Low-pressure air inlet
Object blocking escaping air increases pressure in system
Rise in pressure
Low-pressure air inlet
Escaping air

Figure 2.19 Pneumatic proximity sensor.

9. PROXIMITY SWITCHES

- There are a number of forms of switch which can be activated by the presence of an object in order to give a proximity sensor with an output which is either on or off.

- The micro-switch is a small electrical switch which requires physical contact and a small operating force to close the contacts. Figure 2.20 shows examples of ways such switches can be actuated.



(a) (b) (c)

Figure 2.20 (a) Lever-operated, (b) roller-operated, (c) cam-operated switches.

REED SWITCH

Figure 2.21 shows the basic form of a *reed switch*. It consists of two magnetic switch contacts sealed in a glass tube. When a magnet is brought close to the switch, the magnetic reeds are attracted to each other and close the switch contacts. It is a non-contact proximity switch.

Such a switch is very widely used for checking the closure of doors. It is also used with such devices as tachometers which involve the rotation of a toothed wheel past the reed switch. If one of the teeth has a magnet attached to it, then every time it passes the switch it will momentarily close the contacts and hence produce a current/voltage pulse in the associated electrical circuit.

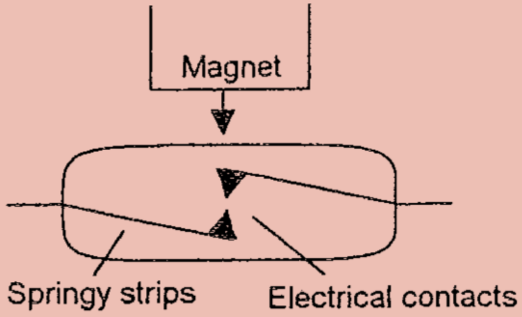
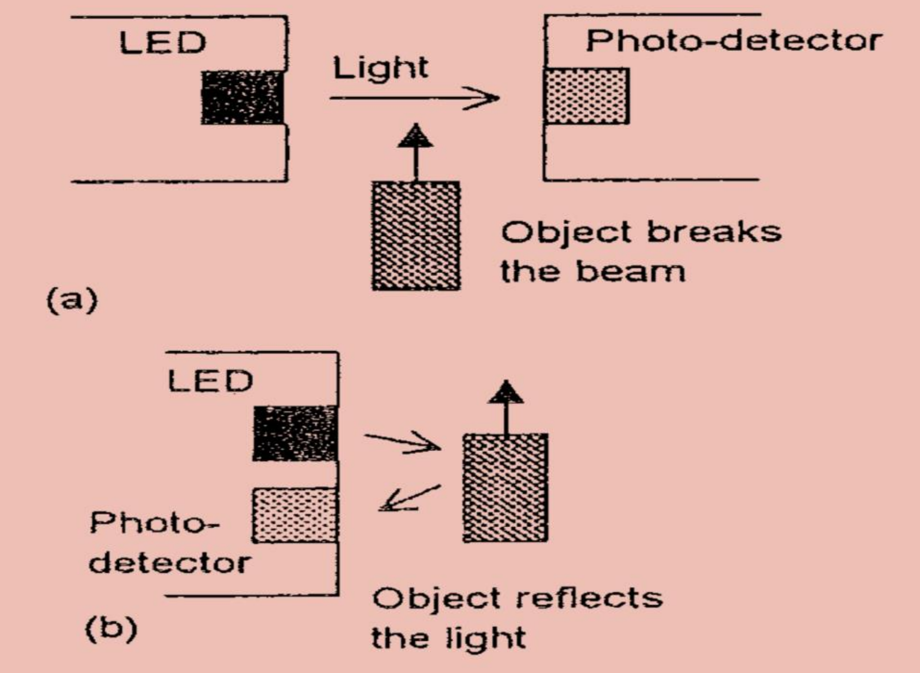


Fig. 2.21 Reed switch

PHOTO SENSITIVE DEVICES

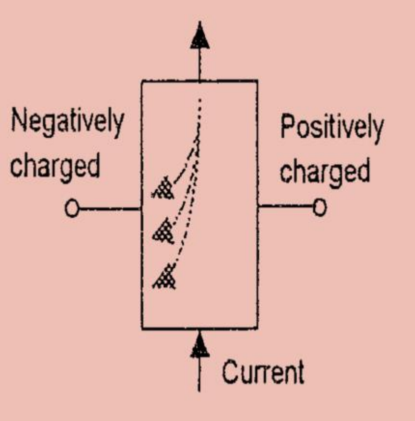
Photosensitive devices can be used to detect the presence of an opaque object by it breaking a beam of light, or infrared radiation, falling on such a device or by detecting the light reflected back by the object (Fig. 2.22).



10. HALL EFFECT SENSORS

❑ .When a beam of charged particles passes through a magnetic field, forces act on the particles and the beam is deflected from its straight line path. A current flowing in a conductor is like a beam of moving charges and thus can be deflected by a magnetic field. This effect was discovered by E.R. Hall in 1879 and is called the *Hall effect*.

❑The Electric field causes charge separation in the conductor and results in its ends to be +vely and -vely charged forming a potential given by,

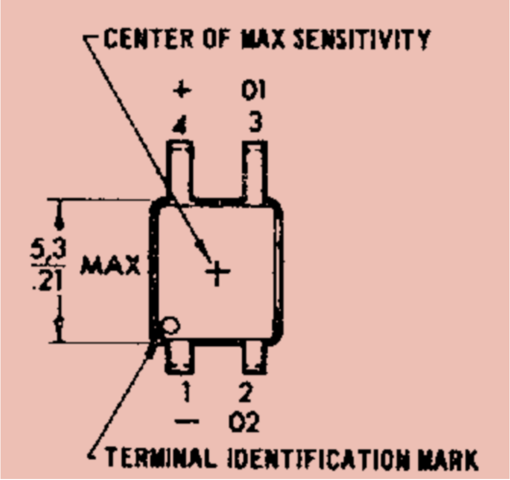


$$V = K_H \frac{BI}{t}$$

where B is the magnetic flux density at right angles to the plate, I the current through it, t the plate thickness and K_H a constant called the *Hall coefficient*. Thus if a constant current source is used with a particular sensor, the Hall voltage is a measure of the magnetic flux density.

6SS ORDER GUIDE

Catalog Listing	634SS2
Supply Voltage (VDC)	4 to 10
Supply Current (mA typ.)	3.5
Output Type	Differential
Output Voltage (V)	1.75 to 2.25 V at 5V, 0 gauss
Sensitivity	(− 400 to + 400 gauss) 0.75 to 1.06 mV/gauss)



APPLICATIONS OF HALL EFFECT SENSORS

Such sensors can be used as position, displacement and proximity sensors if the object being sensed is fitted with a small permanent magnet. As an illustration, such a sensor can be used to determine the level of fuel in an automobile fuel tank.

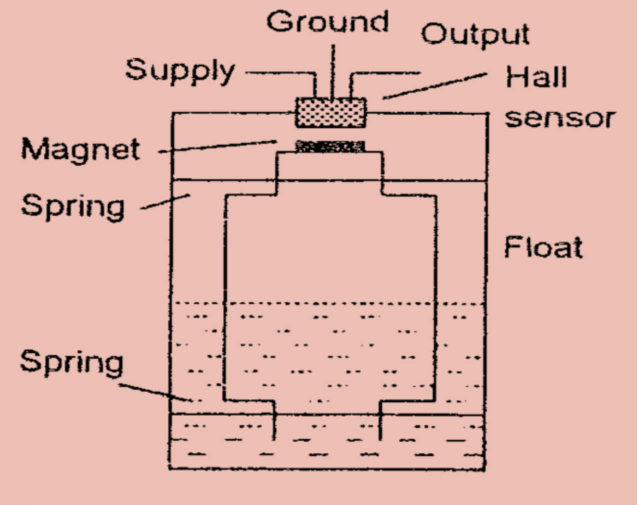


Fig. 2.25 Fluid level detector

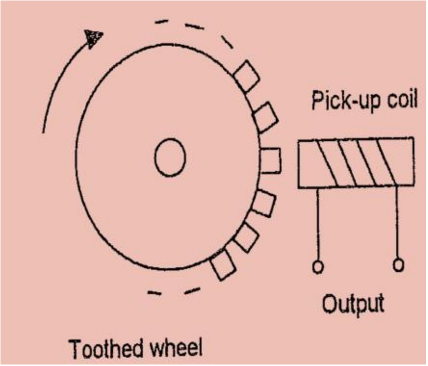
VELOCITY AND MOTION SENSORS

The following are examples of sensors that can be used to monitor linear and angular velocities and detect motion. The application of motion detectors includes security systems used to detect intruders and interactive toys and appliances, e.g. the cash machine screen which becomes active when you get near to it.

Incremental encoder	Optical Encoder discussed previously can be used for measuring the angular velocity by counting the no of pulses being produced.
Tachogenerator	Used to measure angular velocity.

Contd..

the *variable reluctance tachogenerator*, consists of a toothed wheel of ferromagnetic material which is attached to the rotating shaft (Fig. 2.26). A pick-up coil is wound on a permanent magnet. As the wheel rotates, so the teeth move past the coil and the air gap between the coil and the ferromagnetic material changes. We have a magnetic circuit with an air gap which periodically changes. Thus the flux linked by a pick-up coil changes. The resulting cyclic change in the flux linked produces an alternating e.m.f. in the coil.



If the wheel contains n teeth and rotates with an angular velocity ω, then the flux change with time for the coil can be considered to be of the form:

$$\Phi = \Phi_0 + \Phi_a \cos n\omega t$$

Contd..

where Φ_0 is the mean value of the flux and Φ_a the amplitude of the flux variation. The induced e.m.f. e in the N turns of the pick-up coil is thus:

$$e = -N\frac{\mathrm{d}\Phi}{\mathrm{d}t} = -N\frac{\mathrm{d}}{\mathrm{d}t}(\Phi_0 + \Phi_a \cos n\omega t) = N\Phi_a n\omega \sin n\omega t$$

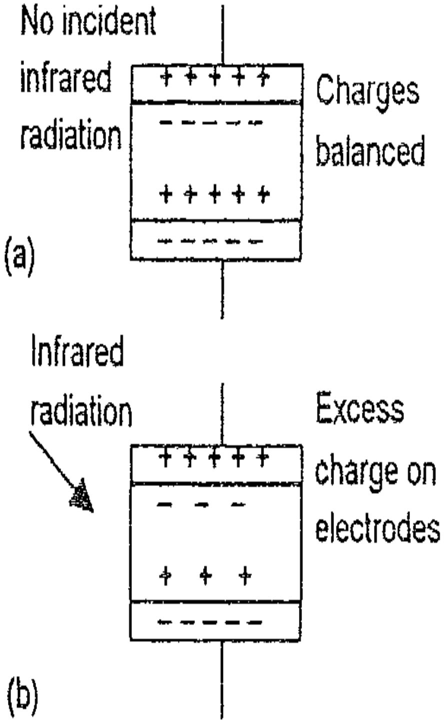
and so we can write:

$$e = E_{\max} \sin \omega t$$

where the maximum value of the induced e.m.f. $E_{\max}$ is $N\Phi_a n\omega$ and so is a measure of the angular velocity.

Pyroelectric sensors

Pyroelectric materials, e.g. lithium tantalate, are crystalline materials which generate charge in response to heat flow. When such a material is heated to a temperature just below the Curie temperature, this being about 610°C for lithium tantalate, in an electric field and the material cooled while remaining in the field, electric dipoles within the material line up and it becomes polarised (Fig. 2.28, (a) leading to (b)). When the field is then removed the material retains its polarisation; the effect is rather like magnetising a piece of iron by exposing it to a magnetic field. When the pyroelectric material is exposed to infrared radiation, its temperature rises and this reduces the amount of polarisation in the material, the dipoles being shaken up more and losing their alignment (Fig. 2.29).



Contd..

Pyroelectric sensor comprises of charged Pyroelectric crystal. If Infrared light is incident on it, its polarization changes and it releases its charge.

when there is a temperature change the change in charge Δq is proportional to the change in temperature Δt:

$$\Delta q = k_p \Delta t$$

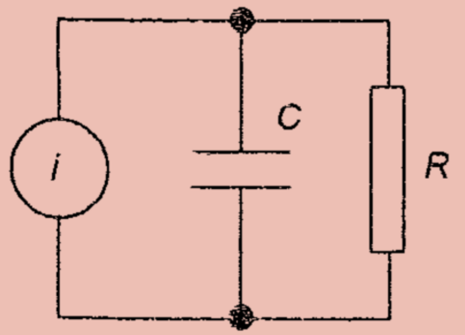
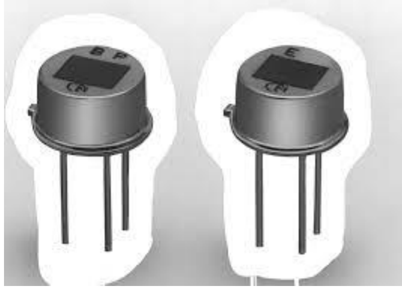


Fig. 2.31 Equivalent circuit

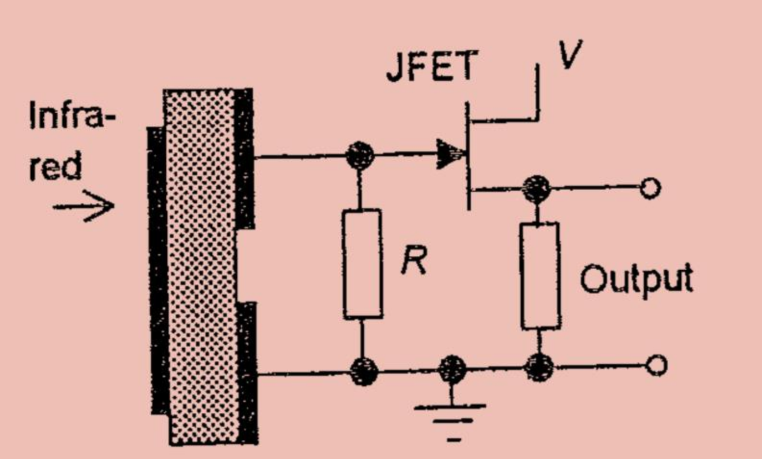
where k_p is a sensitivity constant for the crystal. Figure 2.31 shows the equivalent circuit of a pyroelectric sensor, it effectively being a capacitor charged by the excess charge with a resistance R

For Motion detection multiple pyroelectric electrodes are needed to cancel environmental radiation impact.

- Typically a moving human gives an alternating current of the order of 10^{-12} A. The resistance R has thus to be very high to give a significant voltage. For example, 50 GΩ with such a current gives 50 mV. For this reason a JFET transistor is included in the circuit as a voltage follower in order to bring the output impedance down to a few kΩ.



IRA
E7000



Strain gauge load cell

A very commonly used form of force-measuring transducer is based on the use of electrical resistance strain gauges to monitor the strain produced in some member when stretched, compressed or bent by the application of the force. The arrangement is generally referred to as a *load cell*. Figure 2.33 shows an example of such a cell. This is a cylindrical tube to which strain gauges have been attached. When forces are applied to the cylinder to compress it, then the strain gauges give a resistance change which is a measure of the strain and hence the applied forces.

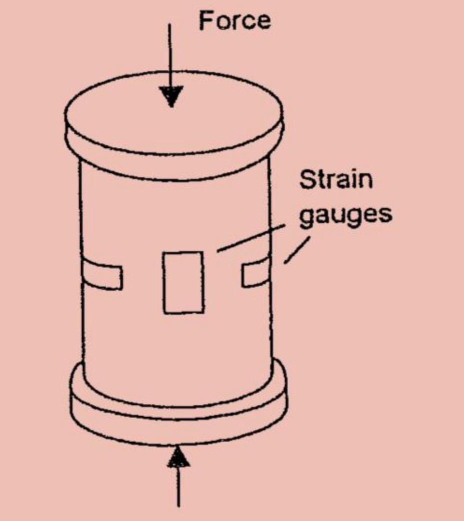


Fig. 2.33 Strain gauge load cell

Fluid pressure

The output voltage is directly proportional to the pressure. Such sensors are available for use for the measurement of absolute pressure (the MX numbering system ends with A, AP, AS or ASX)), differential pressure (the MX numbering system ends with D or DP) and gauge pressure (the MX numbering system ends with GP, GVP, GS, GVS, GSV or GVSX). For example, the MPX2100 series has a pressure range of 100 kPa and with a supply voltage of 16 V, d.c.,

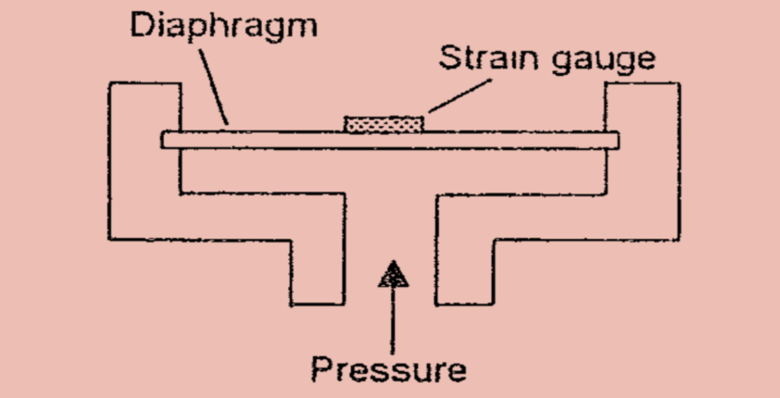


Fig. 2.35 Diaphragm pressure gauge

MPX10D 10kPa Uncompensated Silicon Pressure Sensor Motorola

PIEZO ELECTRIC SENSORS

Piezoelectric materials when stretched or compressed generate electric charges with one face of the material becoming positively charged and the opposite face negatively charged (Fig. 2.40). As a result a voltage is produced.

The net charge q on a surface is proportional to the amount x by which the charges have been displaced, and since the displacement is proportional to the applied force F: $q = kx = SF$

where k is a constant and S a constant termed the *charge sensitivity*. The charge sensitivity depends on the material concerned and the orientation of its crystals. Quartz has a charge sensitivity of 2.2 pC/N . Thus can be used for the measurement of pressure and force

Tactile sensor

A tactile sensor is a particular form of pressure sensor. Such a sensor is used on the 'fingertips' of robotic 'hands' to determine when a 'hand' has come into contact with an object. They are also used for 'touch display' screens where a physical contact has to be sensed.

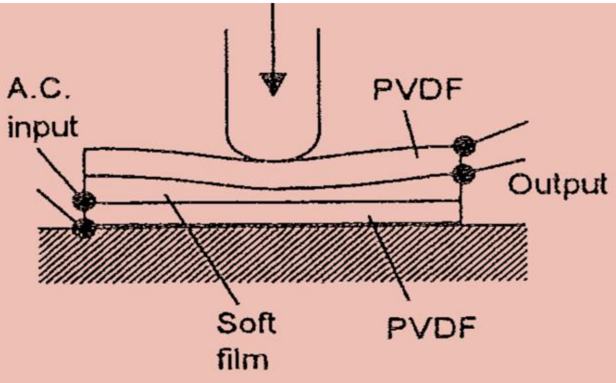
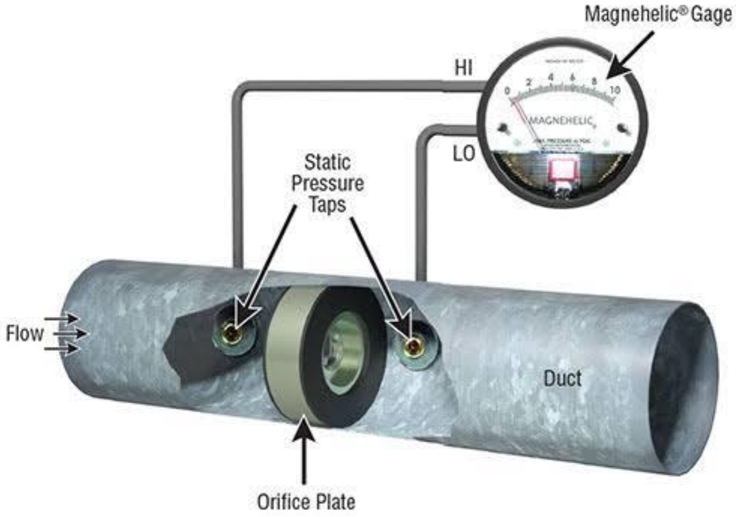


Fig. 2.43 PVDF tactile sensor

One form of tactile sensor uses piezoelectric polyvinylidene fluoride (PVDF) film. Two layers of the film are used and are separated by a soft film which transmits vibrations (Fig. 2.43). The lower PVDF film has an alternating voltage applied to it and this results in mechanical oscillations of the film (the piezoelectric effect described above in reverse). The intermediate film transmits these vibrations to the upper PVDF film. As a consequence of the piezoelectric effect, these vibrations cause an alternating voltage to be produced across the upper film. When pressure is applied to the upper PVDF film its vibrations are affected and the output alternating voltage is changed.

ORIFICE PLATE

- An orifice plate is a device used for measuring flow rate, for reducing pressure or for restricting flow (in the latter two cases it is often called a restriction plate).
- Either a volumetric or mass flow rate may be determined, depending on the calculation associated with the orifice plate.
- It uses the Bernoulli's principle which states that there is a relationship between the pressure of the fluid and the velocity of the fluid.
- When the velocity increases, the pressure decreases and vice versa.



Turbine meter

The turbine flowmeter (Fig. 2.46) consists of a multi-bladed rotor that is supported centrally in the pipe along which the flow occurs. The fluid flow results in rotation of the rotor, the angular velocity being approximately proportional to the flow rate. The rate of revolution of the rotor can be determined using a magnetic pick-up. The pulses are counted and so the number of revolutions of the rotor can be determined. The meter is expensive with an accuracy of typically about ±0.3%.

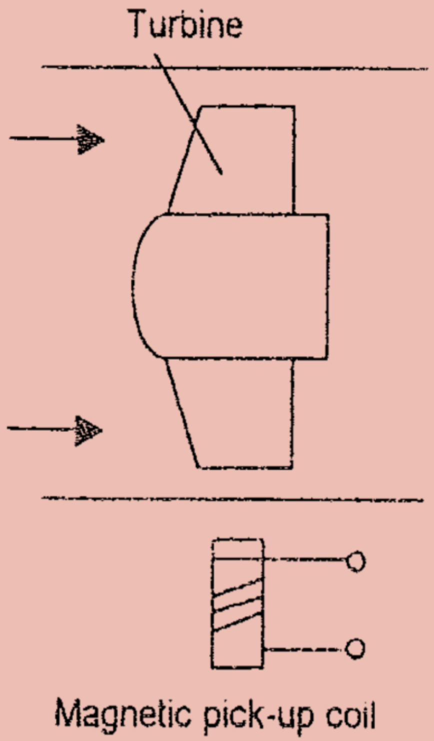
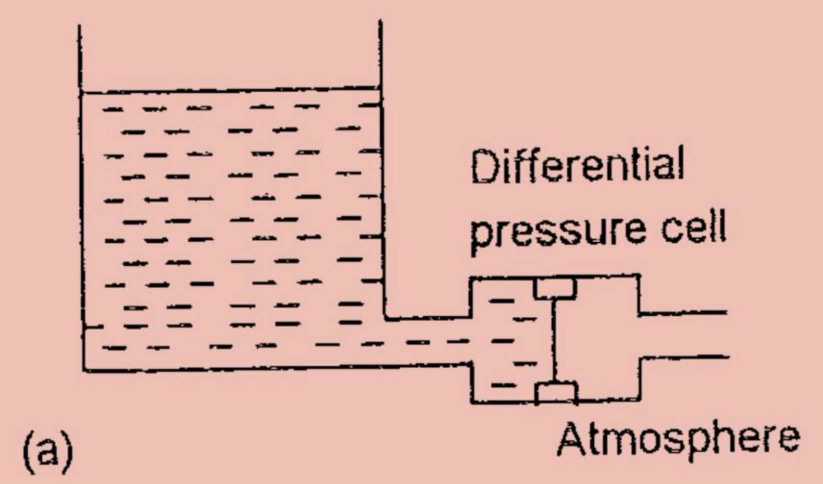


Fig. 2.46 Turbine flowmeter

LIQUID LEVEL MEASUREMENT

- ☐ Monitoring the Float Level
- ☐ Differential Pressure



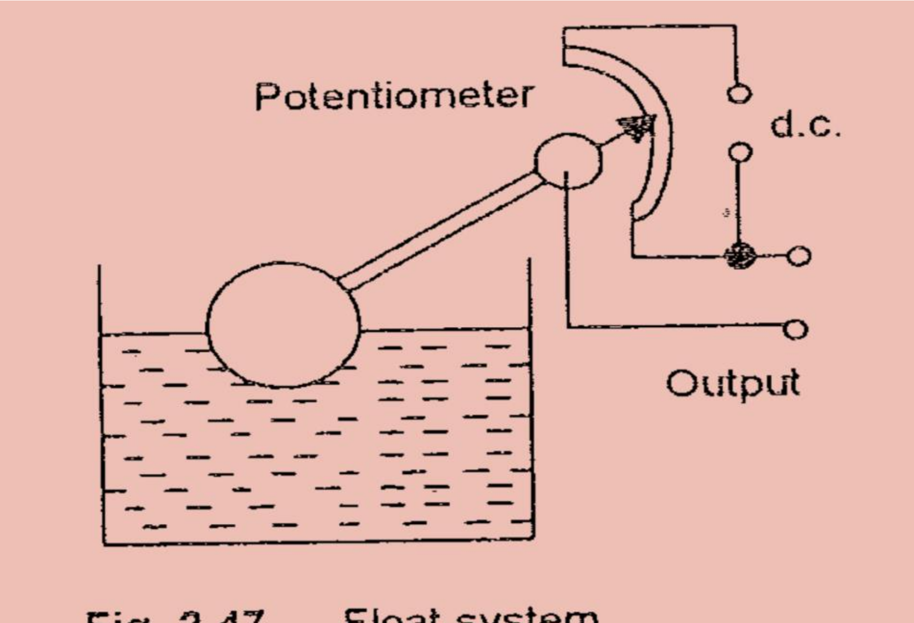


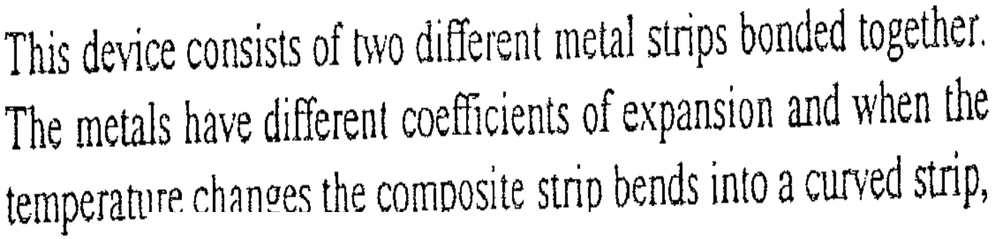
Fig. 2.47 Float system

TEMPERATURE SENSOR

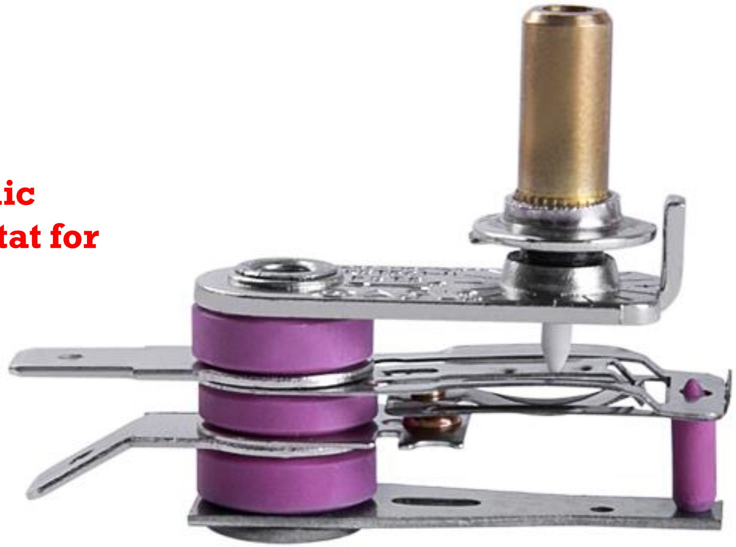
- Temperature sensors appear in building, chemical process plants, engines, appliances, computers, and many other devices that require temperature monitoring

- Many physical phenomena depend on temperature, so we can often measure temperature indirectly by measuring pressure, volume, electrical resistance, and strain

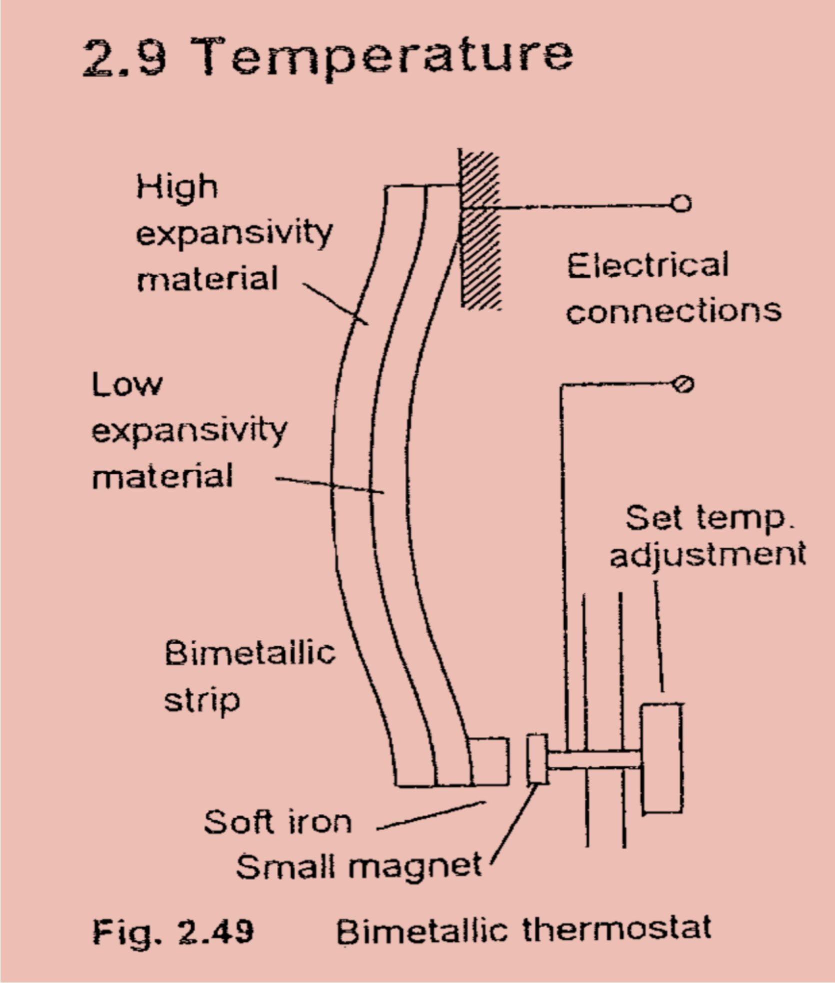
I-METALLIC STRIPS



This device consists of two different metal strips bonded together. The metals have different coefficients of expansion and when the temperature changes the composite strip bends into a curved strip,



Bi-Metallic Thermostat for Iron



2.9 Temperature

Fig. 2.49 Bimetallic thermostat

RESISTANCE TEMPERATURE DETECTORS (RTDS)

The resistance of most metals increases, over a limited temperature range, in a reasonably linear way with temperature (Fig. 2.50). For such a linear relationship:

$$R_t = R_0(1 + \alpha t)$$

where R_t is the resistance at a temperature t °C, R_0 the resistance at 0°C and α a constant for the metal termed the temperature coefficient of resistance. Resistance temperature detectors (RTDs) are simple resistive elements in the form of coils of wire of such metals as platinum, nickel or nickel–copper alloys; platinum is the most widely used.

- **Resistance temperature device.**

$$R = R_0[1+\alpha(T - T_0)]$$

$$R = R_0 e^{\gamma\left[\frac{1}{T}-\frac{1}{T_0}\right]}$$

PT100 RTD (Range 0-1100
Degree Centigrade

THERMISTORS

$$R_t = K e^{\beta/t}$$

Where, K and Beta are constants

Resistance	5-500k
Rated Power	450mW
Technology	Ceramic Composition
Type	Thermal Resistor
Temperature Coefficient	350 ppm
Beta Value	2.6k-4.75k

Thermistors are small pieces of material made from mixtures of metal oxides, such as those of chromium, cobalt, iron, manganese and nickel. These oxides are semiconductors. The material is formed into various forms of element, such as beads, discs and rods (Fig. 2.51). The resistance of conventional metal-oxide thermistors decreases in a very non-linear manner with an increase in temperature, as illustrated in Figure 2.52. Such thermistors having negative temperature coefficients (NTC). Positive temperature coefficient (PTC) thermistors are, however, available.

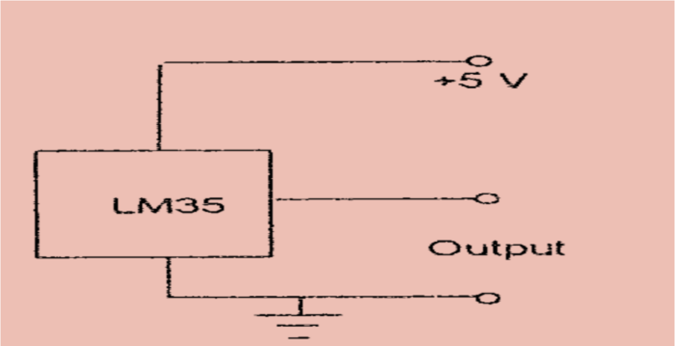
THERMO-DIODES AND TRANSISTORS

junction. Thus when a p–n junction has a potential difference V across it, the current I through the junction is a function of the temperature, being given by:

$$I = I_0(e^{eV/kT} - 1)$$

where T is the temperature on the Kelvin scale, e the charge on an electron, and k and I_0 are constants. By taking logarithms we can write the equation in terms of the voltage as:

$$V = \left(\frac{kT}{e}\right) \ln\left(\frac{I}{I_0} + 1\right)$$



LM311 is Thermo-Diode based. While Thermo-Transistor based is LM35D. Sensitivity is 1mV/^{0}C

THERMOCOUPLE

If two different metals are joined together, a potential difference occurs across the junction. The potential difference depends on the metals used and the temperature of the junction.

Usually one junction is held at 0°C and then.
to a reasonable extent, the following relationship holds:

$$E = at + bt^2$$

where a and b are constants for the metals concerned. Commonly used thermocouples are shown in Table 2.1, with the temperature ranges over which they are generally used and typical sensitivities. These commonly used thermocouples are given

- Suitable for measuring over large ranges

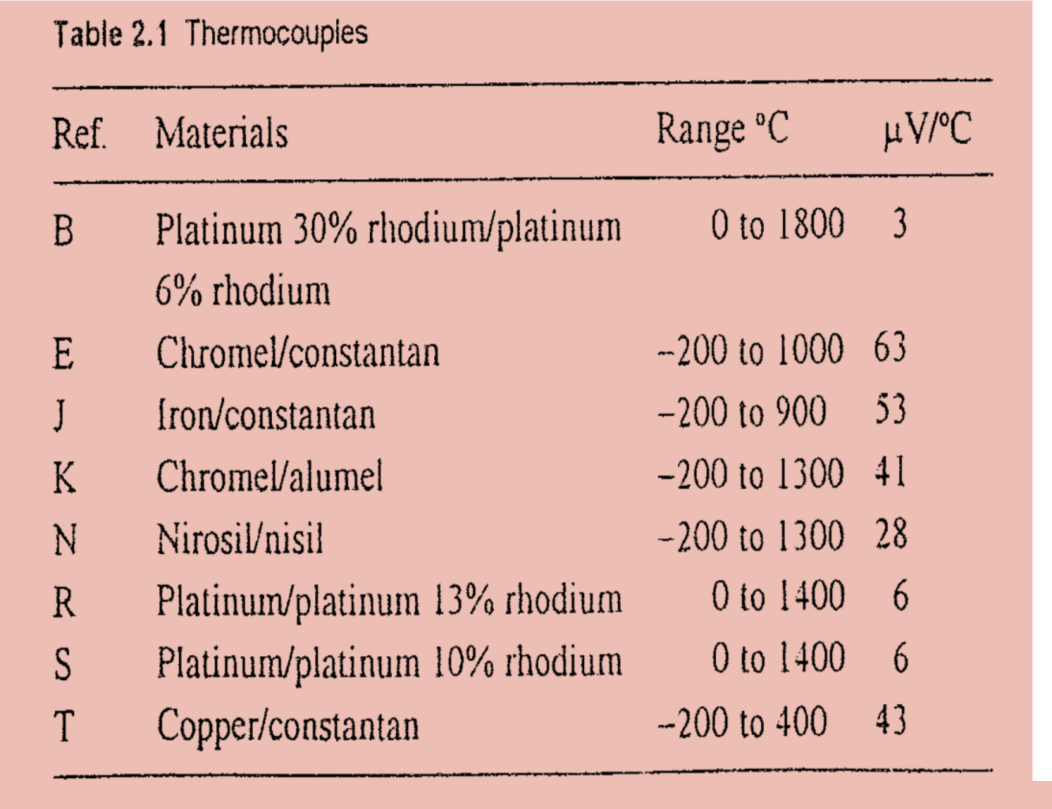


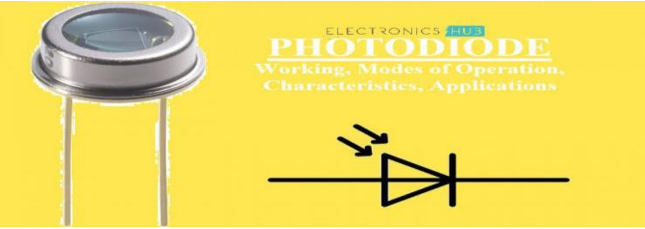
Table 2.1 Thermocouples

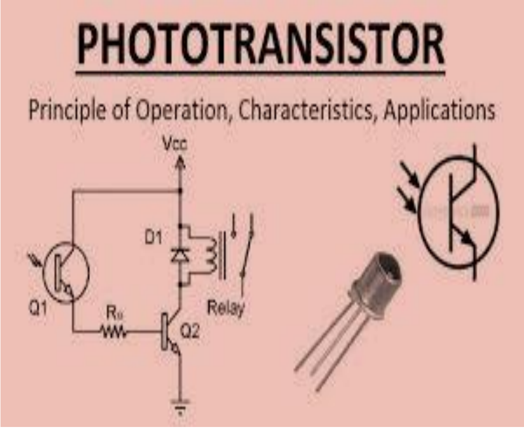
Ref.	Materials	Range °C	µV/°C
B	Platinum 30% rhodium/platinum 6% rhodium	0 to 1800	3
E	Chromel/constantan	−200 to 1000	63
J	Iron/constantan	−200 to 900	53
K	Chromel/alumel	−200 to 1300	41
N	Nirosil/nisil	−200 to 1300	28
R	Platinum/platinum 13% rhodium	0 to 1400	6
S	Platinum/platinum 10% rhodium	0 to 1400	6
T	Copper/constantan	−200 to 400	43

LIGHT SENSORS

- A special type of PN junction device that generates current when exposed to light is known as Photodiode. It is also known as photodetector or photo-sensor. It operates in reverse biased mode and converts light energy into electrical energy.
- The phototransistor is a semiconductor device that is able to sense light levels and alter the current flowing between emitter and collector according to the level of light it receives.
- Phototransistors and photodiodes can both be used for sensing light, but the phototransistor is more sensitive in view of the gain provided by the fact that it is a bipolar transistor. This makes phototransistors more suitable in a number of applications.

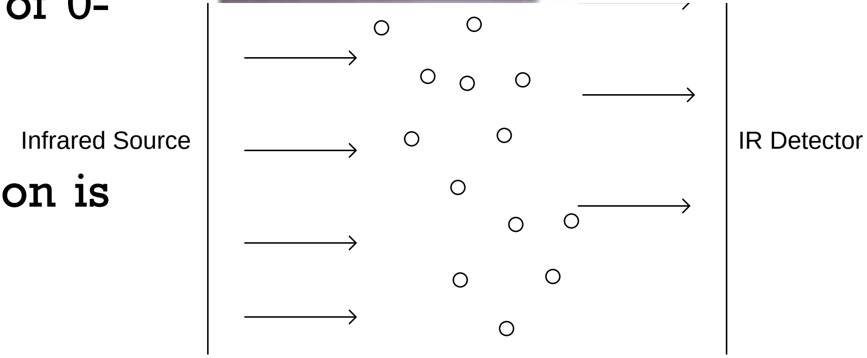
PHOTO DIODES





CO2 GAS SENSOR

- CO2 sensor measures gaseous CO2 levels in an environment
- Measures CO2 levels in the range of 0-5000 ppm
- Monitors how much infrared radiation is absorbed by CO2 molecules



END OF LECTURE # 02

Thank you !!!